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Morphological Changes Induced by Short Pulse Hydrogen Fluoride Laser Radiation on Dental Hard Tissue and Restorative Materials

Bipin C.M. Patel, PhD,[1] and Kenneth R. Rickwood, MPhil[2]*

[1]Department of Dental Health, Dental School, University of Dundee, Dundee, DD1 4HR, Scotland, United Kingdom;
[2]Department of Physics, University of Essex, Colchester CO4 3SQ, United Kingdom

Background and Objective: **The potential benefits of the effects of lasers on dental tissues have yet to be realized but may be brought closer through the availability of a suitable laser. The objective of this project is to examine the surface morphological changes resulting from hydrogen fluoride (HF) laser radiation on tooth and restorative material surfaces.**
Study design/Materials and Methods: **A hydrogen fluoride laser emitting at 2.9 μm is used to interact with a range of dental hard tissue and restorative materials. The surface morphological changes induced by 100 mJ pulses of <1 μs duration is studied using a SEM.**
Results: **The irradiated surfaces displayed microstructures similar to those of a mechanically fractured surface with no evidence of melting.**
Conclusion: **This study suggests that tissue is removed by micro-explosion, leaving a surface free from thermal damage with surface characteristics that would appear to facilitate the adhesion of restorative materials. Lasers Surg. Med. 21:1–6, 1997**

Key words: ablation; dental enamel; dentine; HF laser; SEM

INTRODUCTION

Very early in the history of the medical laser, the application to dental hard tissues was considered. In 1964, Stern and Sognnaes [1] reported that dental enamel could be vaporized by ruby laser light. Since then there have been many reports of investigations into the effects of lasers on dental tissues, described in Lasers in Dentistry by Wigdor et al. [2]. In dental applications, lasers have been advocated to provide a number of clinical benefits that the conventional high-speed turbine lacks. Many of these benefits have yet to be fully realized, e.g., pain-free cavity preparation and the potential for accurate and higher precision work, and new microsurgical techniques have yet to be clinically developed. These potential benefits may be brought closer through the availability of a suitable laser generating non-thermal tissue interaction. Many lasers emit outputs of a wavelength and pulse duration that produce thermal damage to tissue regions adjacent to the irradiated area. In dental hard tissue ablation applications, these effects are undesirable and should be minimised by selecting a wavelength that is highly absorbed and a pulse duration less than the thermal relaxation time. A laser system that fulfils these criteria is the hydrogen fluoride

*Correspondence to: K.R. Rickwood, Department of Physics, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK.

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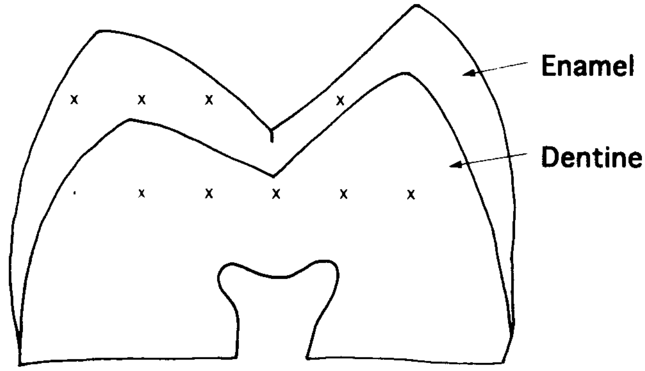

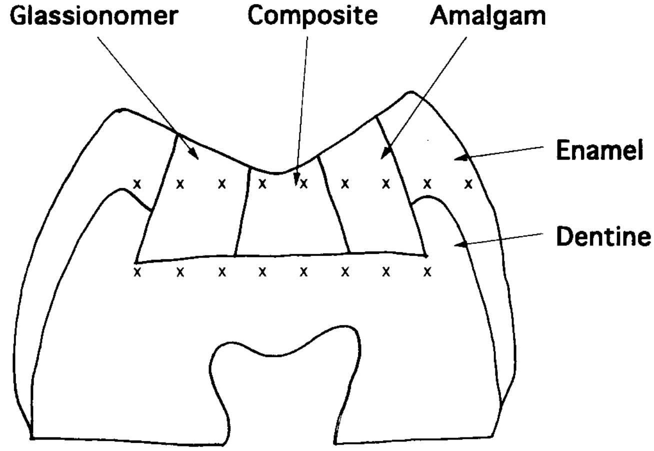

Fig. 1. **A.** Diagram of a longitudinally sectioned tooth showing the location of typical ablation sites. **B.** Diagram of a longitudinally sectioned tooth containing three different restorative materials and showing the location of typical ablation sites.

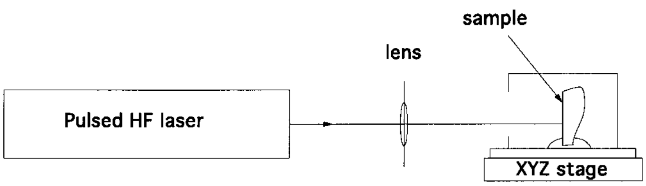

Fig. 2. Experimental setup used for the ablation experiments.

TABLE 1. Hydrogen Fluoride Laser Parameters

Operating gas	SF_6, C_3H_8, He
Pulse repetition frequency	1 Hz
Pulse energy	100 mJ
Pulse duration	1 μs
Fluence per pulse	20 J cm^{-2}

(HF) gas laser. Here, we examine a novel HF laser system to determine its ability to ablate dental hard tissue with the absence of thermal effects.

All three major constituents of dental hard tissue, hydroxyapatite, collagen, and water have absorption peaks in the 2.9 μm region [3–5]. At this wavelength, the thermal relaxation time is of the order of 1 μs [6]. The laser emitting at this wavelength that has been used most extensively is the Er:YAG. A comprehensive account of the research work on this laser and its interaction with dental hard tissue is given by Wigdor et al. [2]. The Er:YAG operating in the normal spiking mode has been used on dental tissue by Hibst and Keller [7] and Li et al. [8]. Used in this mode, the duration the pulse train is ~200 μs, considerably longer than the thermal relaxation time. Shorter Q-switched Er:YAG pulses of ~90 ns duration have been used by Walsh et al. [9] and were found to produce less thermal damage in all tissues examined. The HF laser, which emits at 2.9 μm operating in the pulsed TEA mode, produces pulses of <1 μs duration. These properties may provide ideal laser characteristics for efficient ablation of dental hard tissue without thermal damage. Such pulses have been used by Izatt et al. [10] to ablate calcified tissue (bone) and more recently by Makropoulou et al. [11] to investigate dentine ablation rates.

This report presents the findings of an exploratory investigation into the potential of an experimental HF laser system for machining tooth tissues. A custom HF laser system was constructed with an output up to 150 mJ per pulse, 1–15 Hz pulse repetition frequency, and a pulse duration of <1 μs. The objective was to examine the surface morphological changes resulting from short pulse HF laser radiation on tooth and restorative material surfaces.

MATERIALS AND METHODS

Twenty-five freshly extracted human molar teeth were longitudinally sectioned to reveal a flat enamel, dentine, and pulp cavity (Fig. 1A) and stored in 1% formalin saline. Eight further molar tooth specimens were engineered to contain three standard dental restorative materials in a conventional MOD cavity. Glassionomer, composite, and amalgam were used. The specimens were sectioned longitudinally to reveal a flat surface with all five materials in a single plane (Fig. 1B). The specimens were washed in running water and tis-

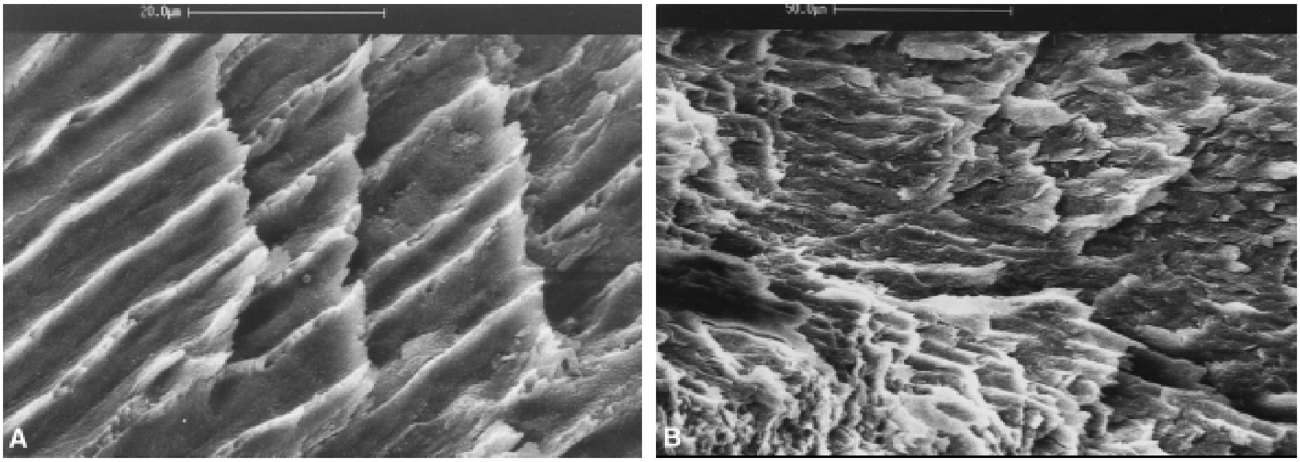

Fig. 3. SEM of enamel after HF laser treatment showing **(A)** microstructure, **(B)** typical ablation site with features similar to those of a mechanically fractured surface.

sue dried prior to insertion into the laser irradiation mount.

The TEA HF laser, of the corona preionization type developed from those described by Serafetinides et al. [12], operated with a gas mix of sulphur hexafluoride and propane in a helium carrier. The exhaust gas, containing a small percentage of HF (~0.1%), was scrubbed and neutralised before venting to air. The multiline pulses in the wavelength range 2.6–3.1 μm and 1 μs duration, measured with an n-type GaP detector, were produced at a pulse repetition frequency of 1 Hz.

The laser output beam was focused using a 100 mm focal length CaF_2 lens to produce an irradiated area of 0.5mm^2, which corresponds to a spot diameter of 400 μm. The experimental setup used is shown in Figure 2. The pulse energy, measured with a Gentec ED-200 joulemeter, was 100 mJ. This gave an energy density at the sample of 20 J cm^{-2}. This corresponds to a fluence in the range of that used by other workers at this wavelength [7,9–11]. The principal parameters of the laser used in this study are presented in Table 1.

The horizontal laser beam was focused onto a sectioned flat sample surface mounted in a partially enclosed holder attached to an adjustable XYZ table. Samples of dentine, enamel, and restorative materials were irradiated with between 1 and 10 pulses. The irradiated samples were examined using a Cambridge Stereoscan 360 scanning electron microscope.

RESULTS

At the site of irradiation, lesions were confined to an area the shape and size of the focused spot of ~ 0.5 mm^2. During irradiation, a high intensity white light was emitted from the site of the laser light-tissue interaction region. This is attributed to the formation of a plasma and is commonly observed with lasers operating in the pulsed mode. All irradiated surfaces examined show microstructures similar to those resulting from mechanical fracture. The samples show no rounded edges or charring.

Enamel

Lesions are formed with clean sharp edges with no discoloration. There appears to be no melting and resolidification of ablation products within the ablated area. The surface shows the classic enamel micro-structure with a discrete hydroxyapatite crystalline arrangement (Fig. 3). The pattern is very similar to that revealed through mechanical fracture.

Dentine

Lesions are formed with clean sharp edges with no discoloration. SEM examination reveals an intact open dentinal tubule microstructure (Fig. 4). On occasions signs of collagen bundles were also present adjacent to open tubules (Fig. 5). There was no evidence of melting or resolidification products.

Caries

Lesions are formed with clean sharp edges with no charring, burning, or discoloration. There appeared to be no change in the micro structure at the ablation site.

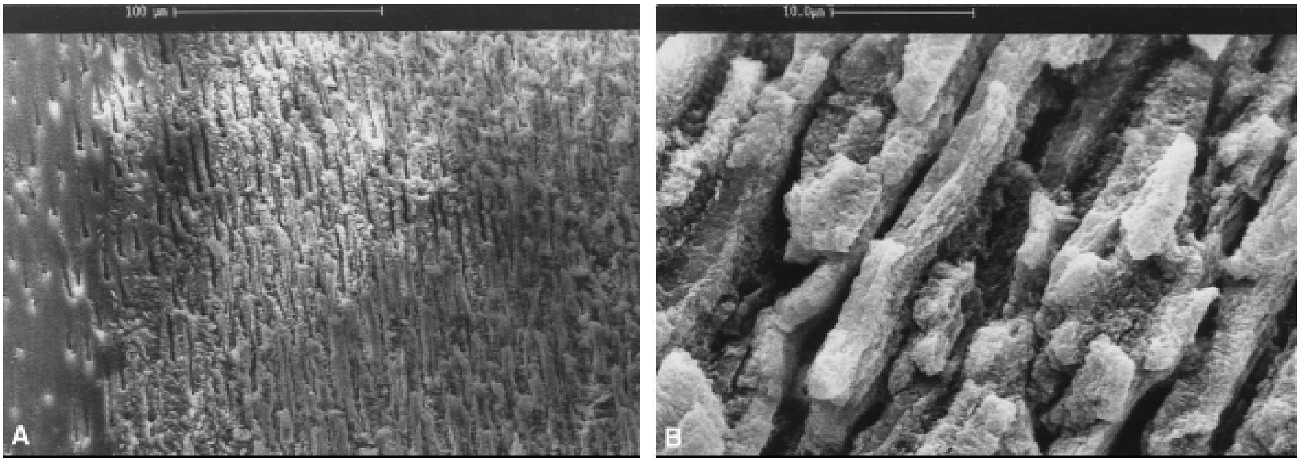

Fig. 4. SEM of dentine after HF laser treatment showing **(A)** open tubule structure on the right, unablated region on the left, **(B)** intact open tubules.

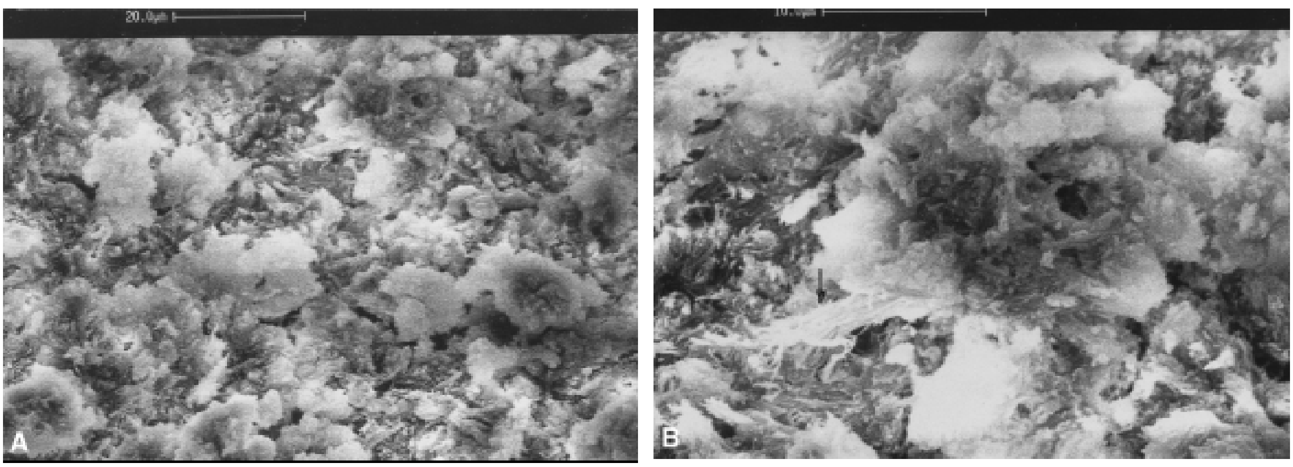

Fig. 5. SEM of dentine after HF laser treatment showing collagen bundles adjacent to open tubules **(A)** ×1200, **(B)** ×3000.

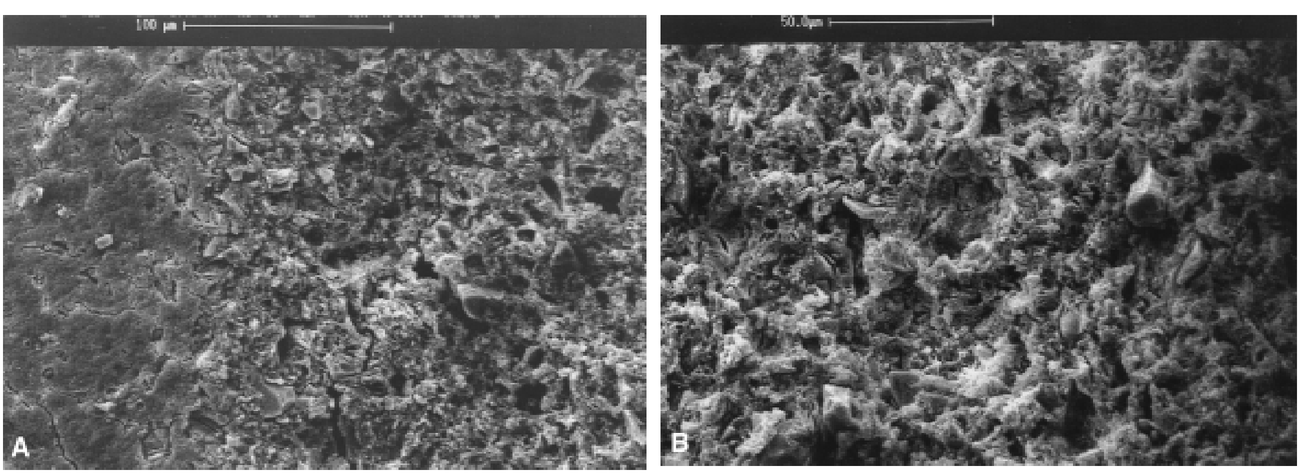

Fig. 6. SEM of glassionomer after HF laser treatment showing **(A)** glass particulate structure on the right, unablated region on the left, **(B)** matrix structure containing glass particles showing absence of melting and carbonisation.

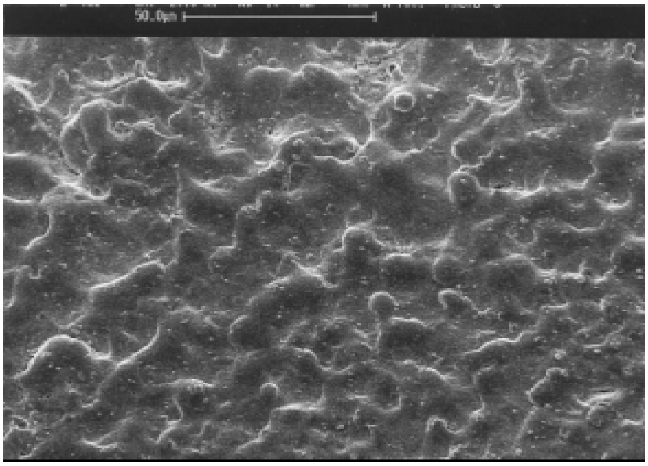

Fig. 7. SEM of amalgam after HF laser treatment showing a solidified wavelike pattern.

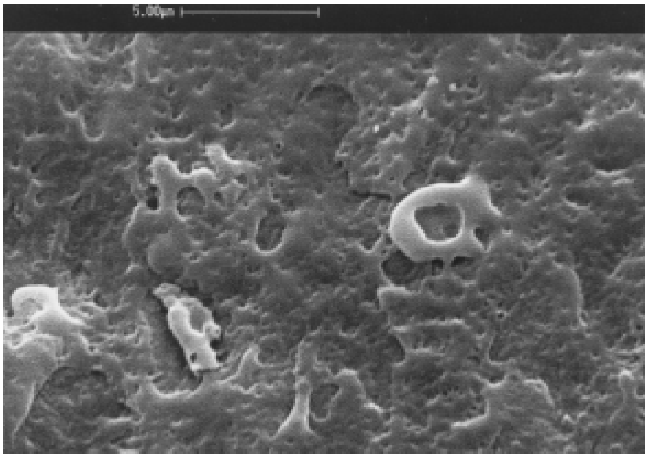

Fig. 8. Resolidified film adjacent to irradiated site on enamel.

Composite

Lesions are formed with clean sharp edges with no charring, burning, or discoloration. The micro structure shows the matrix with glass particles and no signs of melting.

Glassionomer

Lesions are formed with clean sharp edges with no charring, burning, or discoloration. The embedded glass particulate structure, with the clear absence of melting, can be seen in the micro structure (Fig. 6).

Amalgam

There is no obvious lesion formation, but a black residue is deposited around the site of irradiation. The irradiated area shows a solidified wavelike pattern (Fig. 7).

Close examination of the sample surfaces adjacent to the irradiation sites show no deposits with the exception of amalgam as described above and enamel where a resolidified pitted thin-film structure was apparent (Fig. 8).

DISCUSSION

The surface structures exposed by the HF laser action at 2.9 μm in enamel and dentine are remarkably similar to those resulting from a fractured or phosphoric acid etched specimen. These observations together with the lack of burning, charring, and general carbonisation indicate that the ablation mechanisms underlying the HF laser-substrate interaction are dissimilar to those of infrared laser systems operating at different wavelengths. For example, in lasers such as CO_2 and Nd:YAG, the interaction is considered to be thermal. The material is vaporized through melting and boiling processes as a result of a rapid rise in temperature. The remaining substrate surface is irreversibly altered in physical composition and may be dehydrated. In addition, thermal energy is dissipated via conduction and diffusion into the surrounding tissue. This has been the major factor limiting the use of such systems in the clinical environment. The Er:YAG laser operating at 2.94 μm in the Q-switched mode, which has a similar wavelength and pulse duration to the HF, has been shown to produce less thermal damage than the normal longer Er:YAG pulses [9].

The combination of short pulse duration and midinfra-red wavelength in the 2.9 μm band provided by the HF system gives a significant advantage over conventional infra-red lasers. The laser pulse-tissue interaction time is confined within the pulse duration. Thus thermal energy is lost with the ablated materials.

The morphology revealed by HF laser irradiation appears to support the microexplosion theory of tissue removal. In the study of the ablation of bone by HF laser radiation, Izatt [10] suggests that the mechanism of tissue removal is that the low boiling point constituents, water (100°C) and collagen (~200°C), are rapidly decomposed and vaporized. The rapidly expanding vapour then entrains solid particles of the high melting point (1670°C) hydroxyapatite. This explosive method of tissue removal is consistent with the fracture like nature of the surfaces examined in this study. The short pulse duration also ensures that the ablation products carry away the deposited thermal energy. The combina-

tion of high absorption at 2.9 μm and short pulse length generates a surface that is similar to that produced by excimer laser photoablation [13].

CONCLUSIONS

These preliminary investigations indicate that the unique features of HF laser facilitate the ablation of enamel and dentine without melting and resolidification of hydroxyapatite at the crystalline level. The edge of the lesion was sharp and clean with no detectable thermal damage. The cut walls presented apatite crystalline surfaces.

The quality of cut in comparison with the other infra-red lasers appears to be very high and may be compared with that of an excimer laser ablation [13]. Thus the HF laser has the potential for fine and accurate cutting. In addition, there appears to be no detrimental effects on tissue immediately peripheral to the ablation site.

The result of the interaction of HF laser radiation with enamel and dentine is a surface similar to that produced by fracture or acid etch. Such a surface is absent of a smear layer and presents a natural intact structure for the adhesion of restorative materials. We are currently conducting detailed studies to ascertain potential clinical requirements of laser parameters for efficient rates of healthy/diseased dental hard tissue removal.

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